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TECHNICAL REPORT DRCPM-HEL-79-6

THERMAL MARKING OF HEAVY STEEL
ARMOR WITH HIGH ENERGY LASERS

Vernon A. Nieberlein
High Energy Laser Laboratory

28 September 1979

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

A theoretical analysis has been made of the thermal marking process as applied to cold tanks and other ordnance involving heavy armor. The effects of laser power, irradiation time, seeker characteristics, atmospheric conditions and angle of incidence on the maximum range and forget times were calculated. A comparison is made with the technique of using the same seeker on an unmarked hot tank, and with using the thermal marking process as a supplement to the radiation from a hot tank. Results are given in graphic form.

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ILLUSTRATIONS

1. INTRODUCTION

Thermal marking is a technique for missile guidance which uses a high energy laser. This technique employs the laser to create a hot spot on the target, which may be a tank, an armored personnel carrier, a self-propelled artillery piece, etc. The hot spot emits thermal energy during irradiation by the laser and continues to emit for some time after the laser is turned off, while the spot is cooling down. Conventional missile seekers can lock onto this radiant energy so long as its intensity is above a certain threshold level. As the hot spot cools down the emitted energy falls off, but this may be compensated for by the closing in of the missile in flight. Whether or not this compensation is sufficient to maintain lock on depends on the speed of the missile, the type of seeker, atmospheric conditions, emissivity of the target, intensity of the laser beam, its angle of incidence on the target, and the length of irradiation by the laser.

The rates of heating and cooling of laser heated targets were investigated experimentally by Holl and McClusky [1] in 1971. These experiments, however, were performed with a low energy laser on sheet lead. Nevertheless the results were useful in showing the shape of the isotherms during the heating and cooling cycles. Kast [2] investigated theoretically the thermal marking process using a high energy laser. He developed a computer code for this purpose but the number of variables investigated was limited. Wachs and Jenkins [3] irradiated a thick (six inches) steel slab with a high energy laser and determined the isotherm contours and the heating and cooling rates. They also determined the capability of operational seekers to lock onto a hot spot. All of these investigations were of a preliminary nature, but showed that the thermal marking concept possessed some feasibility. A more extensive examination of this feasibility has been undertaken in the present theoretical work.

2. THE MODEL

The system model is shown in *Figure 1*. This illustration shows a tank as the target at the left. At the right, a high energy laser is irradiating the target to form a hot spot which in turn emits energy. The wavelength of the laser energy for the purposes of this analysis was chosen to be 10.6 μm, while the emitted energy is of course a spectrum of wavelengths as given by Planck's Law. In the vicinity of the laser stands a missile equipped with a typical modern seeker. This seeker has a minimum threshold value for the energy which it can detect radiating from the hot spot, and this energy must lie between two sharply defined limits of wavelength. The intensity of the radiation from the hot spot varies directionally according to Lambert's Law and inversely as the square of the distance from the source. To illustrate, the arc moving away from the tank in *Figure 1* is an imaginary surface or envelope where the radiant energy from the hot spot is just that necessary for the seeker to be able to lock onto the target. As the temperature of the hot spot increases, this envelope recedes still further from the target.

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At the instant of lockon, as shown in *Figure 1*, the missile is fired, but the laser is not shut off, allowing the envelope to recede well behind the missile. At the point shown in *Figure 2* the laser is cut off, but the missile has been in flight for a period of about one second, placing it well within the minimum energy envelope. This "head-start" of the missile is necessary because the envelope collapses very rapidly - much faster than the velocity of the missile - for the first second or so after the laser is turned off. At the "critical point", as shown in *Figure 3*, the minimum energy envelope has caught up with the missile, but has not passed it. From this point on, the collapse of the envelope has slowed down sufficiently so that the missile is able to stay ahead of it. *Figure 4* shows the collapsing envelope well behind the missile at the moment of impact.

3. BASIC EQUATIONS

To get the surface temperatures within the hot spot and its surrounding area and the temperature profile into the target, a finite-difference computer program was written. The program considered heat losses from the surface by conduction to the interior, by lateral conduction, and by radiation. Heat losses by natural convection were insignificant and ignored. The backside temperature was also calculated. The central temperature of the hot spot was then used to calculate the range from the target to the envelope of minimum energy required for lockon. Referring to *Figure 5*, there is a heat-seeking missile approaching a hot spot. Lambert's cosine law states that the energy per unit of time (dQ_1), radiated from an element of area in the hot spot (dA_1), into the solid angle $\sin\zeta \, d\zeta \, d\xi$ will be

$$dQ_1 = \left(\frac{\sigma T^4}{\pi} \cos\zeta \right) dA_1 \sin\zeta \, d\zeta \, d\xi \quad , \tag{1}$$

where σ is the Stefan - Boltzmann constant and T is the temperature of the hot spot. Of this amount, the fraction intercepted by dA_2, an element of area on the sensor, is

$$\frac{dA_2 \cos\theta}{R^2 \sin\zeta \, d\zeta \, d\xi} \tag{2}$$

where R is the missile-target distance. The quantity of energy per unit time impinging on the element dA_2 is therefore the product of (1) and (2).

$$dQ_2 = \frac{\sigma T^4}{\pi} \frac{\cos\zeta \cos\theta}{R^2} dA_1 \, dA_2 \quad . \tag{3}$$

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We may presume that the sensor will always align the missile along the path R so that $\cos\theta = 1$. Also, the energy flux falling on the sensor from the entire hot spot is that described by (3) if one integrates over the whole hot spot area. Thus (3) becomes

$$\frac{dQ_2}{dA_2} = \frac{\sigma T^4 \cos\zeta}{\pi R^2} \int dA_1 .$$ (4)

But the integral in (4) is simply the area of the hot spot which, if the laser is in the vicinity of the missile, is an ellipse with an area of $\dfrac{1}{\cos\zeta}$ $\dfrac{\pi D^2}{4}$ where D is the diameter of the laser beam.

Substituting, (4) becomes

$$\frac{dQ_2}{dA_2} = \frac{\sigma T^4 D^2}{4R^2} .$$ (5)

Equation (5) describes the energy flux impinging on the sensor, but this element cannot "see" all of it. The sensor functions on only a fraction of the total spectrum lying between two specified wavelengths of λ_1, and λ_2. Plank's distribution law gives the amount of energy seen as

$$q_\lambda = 2\pi c^2 h \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda^5 \left(e^{ch/\lambda KT} \underline{-} 1\right)} .$$ (6)

Where c is the speed of light, h is Planck's constant and k is the Boltzmann constant. The fraction of the total spectrum seen is then $\dfrac{q\lambda}{\sigma T^4}$. Finally, the hot spot is not a black body, but has the emissivity ϵ. When the above expressions are placed in (5) and the result is solved for R the equation is

$$R = \sqrt{\frac{\pi c^2 h D^2 \epsilon}{2 \cdot 10^7 (dQ_2/dA_2)} \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda^5 \left(e^{ch/\lambda KT} \underline{-} 1\right)}} .$$ (7)

Equation (7) gives the range, or distance from the hot spot, of the missile when it is receiving an arbitrary energy flux of dQ_2/dA_2. If dQ_2/DA_2 is chosen to be the minimum for which the seeker will operate, then (7) gives the maximum range for lockon. The factor 10^7 in the denominator of (7) makes the equation dimensionally correct if h is given in erg sec and

dQ/dA is given in watts cm⁻². As stated, the finite-difference portion of the computer program supplied the value for T, as a function of laser power, beam diameter, angle of incidence, attenuation by weather, length of irradiation, and absorptivity of the incident energy. In all cases, the laser was presumed to be in the vicinity of the launcher.

4. DETERMINATION OF MAXIMUM MISSILE RANGE AND FORGET TIME

Values of T were computed and from these were obtained values for R which were plotted against time, as in *Figure 6*. What might be a typical value for modern seekers, dQ/dA was chosen to be 2.7×10^{11} watts cm⁻² times the signal-to-noise ratio. In the example shown in *Figure 6*, the solid line is the location from the target in meters of the minimum energy envelope. The missile must stay as close, or closer to the target than this envelope at all parts of its flight in order to maintain lockon. A missile on a launcher 1550 meters from the target senses the energy after the laser has irradiated the target for 3.9 seconds, and is immediately launched from point A. At five seconds the laser is turned off and the missile is now 1340 meters from the target. At six seconds (or one second after laser cutoff) the minimum energy envelope has caught up with the missile at 1100 meters from the target (the critical point). From here on, the missile is faster than the collapsing envelope and it impacts the target at B, after a total of 7.9 seconds for the entire operation. To get the maximum missile ranges, such graphs were drawn for every combination of variables.

It can be seen that, once the laser has been shut off, the system has fire-and-forget capabilities. In the example of *Figure 6*, the time between five seconds (the laser cutoff) and 7.9 seconds (the point of impact), the system requires no attention. In regard to this fire-and-forget capability a trade-off can and must be made between a system giving maximum range, or one giving maximum forget time. The present analysis gives maximum range, which results from a system that fires the missile at the moment of lockon, about a second or so before the laser is turned off. The forget time is therefore shortened about a second less than maximum, which would be the full flight time of the missile. A different approach is that of Kast [2] who maximized forget time at the expense of range by firing the missile at the moment of laser cutoff. Returning to *Figure 6* the dotted line shows the path of such a system. Using the flight path of the same missile as that launched at A, the missile is now launched at C, the moment the laser is cut off. This missile must be placed no farther from the target than 1260 meters in order to stay within the minimum energy envelope at the critical point. It impacts the target at D, 8.6 seconds after the laser was turned on. Thus the forget time has been increased from 2.9 seconds to 3.6 seconds, but the maximum range has been reduced from 1550 meters to 1260 meters.

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Using a procedure which gives maximum missile range, typical forget times are illustrated in Figure 7. The bars labeled "burn" or "burn time" represent the time that the laser irradiates the target. There is some overlapping with the flight time. The difference between the end of the burn time and the end of the flight time is the forget time.

5. RESULTS

For all cases an absorptivity of 0.5 was used in calculating the temperature of the hot spot, that is, 50 percent of the laser energy was estimated to be absorbed by the target and the remainder reflected. Likewise the emissivity of the hot spot in all cases was estimated to be 0.5. These values are known to change somewhat with temperature, but for the purposes of this analysis they were assumed to be constant. The laser beam size in all cases was taken to be 5 cm in diameter. The incident laser flux was presumed to be a step function where 63.21 percent of the energy fell uniformly within the nominal spot diameter and the balance fell outside this, but uniformly within two diameters. The fraction 0.6321 is of course the height of a step function which forms a cylindrical volume equal to the volume under a Gaussian surface and within the same nominal diameter as the cylinder. A step function was used rather than a Gaussian distribution because it was felt that this represented the actual case better. Experimental evidence has shown the flux peak to wander about, so that the time-averaged flux is not Gaussian. The target was assumed to be steel with a thickness of three inches and an initial temperature of 0 degrees Centigrade. Other variables are given on the individual illustrations.

As stated, for this analysis a minimum threshold energy value which would permit the seeker to function was chosen to be 2.7×10^{-11} watts cm^{-2}. The seeker would have a noise value equivalent to this strength of signal, so a signal of this strength might be discernible, but not necessarily strong enough to maintain lockon. A higher specified minimum signal-to-noise ratio must therefore be chosen to reliably maintain lockon. The signal-to-noise ratio times 2.7×10^{-11} is therefore the minimum energy level used for dQ_2/dA_2 in Equation (7). Figure 8 shows the effect of signal-to-noise ratio on the maximum missile range. Also in this figure the dashed lines show the maximum range for sensing a hot M60 tank without the benefit of thermal marking. By a "hot" tank is meant one which has had the engine running for an extended period of time. A "suppressed" tank is one which has had the engine compartment and other hot areas modified so as to shield the emission of thermal energy. By experience, signal-to-noise ratios of less than five do not appear practical, so the majority of calculations were performed using this value. In Figure 9 the forget time for a suppressed or unsuppressed tank not using thermal marking is simply the flight time of the missile, since no laser operation is involved. Crossing the dashed lines in Figure 9 is a short dividing line which marks the forget

time for the maximum available range for this system sensing a supressed hot tank without the benefit of thermal marking. Beyond this on the dashed lines are the forget times for an unsuppressed hot tank. The solid lines are, of course, the forget times using thermal marking on a cold tank.

In *Figure 10* the effect of angle of incidence is shown. The solid lines indicate the advantage that can be gained if one aims the laser normal to a target surface. If the orientation of the surface cannot be determined, 50 degrees can be used as an "average" angle of incidence. This is because the bounded surface area of a hemisphere intersected by a central cone of 101 degrees (50.5 degrees either side of normal) is equal to the hemispherical area lying outside the cone. Thus a random laser shot at an unknown orientation has an equal chance of falling inside or outside such a cone. It may be presumed that if the target is visible, the angle of incidence will be better than average, and, for most of the calculations in this study, an angle of incidence of 30 degrees was used. The curve for normal angle of incidence ends at a laser irradiation time of eight seconds because the target absorbed enough energy under these conditions to start melting the steel. It is not profitable to continue irradiating the target after melting begins as the surface temperature will not appreciably increase and therefore the maximum tracking range will not increase. *Figure 11* gives the forget times for various angles of incidence as shown by the solid lines. The dashed line is again the forget time for a suppressed and unsuppressed hot tank without the benefit of thermal marking. In this case, there is no angle of incidence since no laser beam is involved.

Figure 12 gives the effect of atmospheric conditions on the maximum range. Three types of conditions were examined, clear, hazy, and very hazy. These were defined by visibilities of 23 km, 8 km, and 3 km respectively. Atmospheric conditions attenuated both the laser beam and the emitted energy from the hot spot but by different amounts because of the difference in wavelengths. Most of the calculations were performed using a hazy atmosphere. *Figure 13* shows the effects of atmospheric conditions on forget time and also the expected forget times using the same missile and sensor on a hot tank, without the benefit of thermal marking. *Figures 14* and *15* show the effects of irradiation times at various laser power levels on the maximum range and forget times respectively. *Figure 16* gives the same information as *Figure 14* but it is plotted in a more usable form. It can be readily seen from *Figure 16* that to fire a missile from 1600 meters, the following options are available: 10 seconds of irradiation at 34kW; 9 seconds at 36kW; 8 seconds at 38kW; 7 seconds at 40kW; 6 seconds at 44kW; 5 seconds at 49kW; 4 seconds at 57kW; or 3 seconds at about 69kW.

The effect of different seekers was briefly explored. Using the same missile flight characteristics, the seeker wavelength band or window was moved from 5-5.8 μ down to

1.1-8 μ in steps of one micron. The results are shown in *Figure 17*. The significant observation from this illustration is this: If one keeps the irradiation time short, i.e., two seconds, then the 4-4.8 μ band will give maximum range. However, for the longer irradiation times, like 10 seconds, the 2-2.8 μ band is the optimum wavelength.

Finally, a brief investigation was made into the effect of using thermal marking as a supplement to the radiation from a hot M-60 tank - both suppressed and unsuppressed. While a seeker of the type used in this study would lockon to a hot tank (one whose engine has been running for a prolonged period), the lockon was improved if assisted by thermal marking. A 10-second irradiation time at 50,000 watts increased the maximum available range 36 percent for the unsuppressed tank and the same conditions on a suppressed tank increased the maximum range 113 percent. The results are given in *Figure 18*.

6   CONCLUSIONS

A.   It is feasible to mark a cold tank or other armored target with a high energy laser and track on the hot spot after the laser has been turned off.

B.   For a supersonic missile with a modern seeker, the maximum range is in the vicinity of 2000 meters, limited by the melting point of steel.

C.   The system provides forget times in the vicinity of three seconds.

D.   Weather has an appreciable effect. The above conclusions are based on a visibility of eight kilometers. Unusually clear or unusually hazy days affect the maximum range by 20 percent.

E.   Increasing laser power does not increase the maximum range of the system, but decreases the necessary irradiation time to achieve maximum range.

F.   If an irradiation time of five seconds can be tolerated, a laser power of 70,000 watts will give the maximum range of 2000 meters.

G.   The system can be used to advantage on hot tanks by supplementing the radiation. The advantage can be as much as 700 meters for an unsuppressed tank, and 1200 meters for a suppressed tank, using 50,000 watts in a 5 cm beam.

H.   Ways to increase the range would be:

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- Develop means to operate reliably at a signal-to-noise ratio of 1.

- Increase the speed of the missile.

- Use a seeker with a very wide band width.

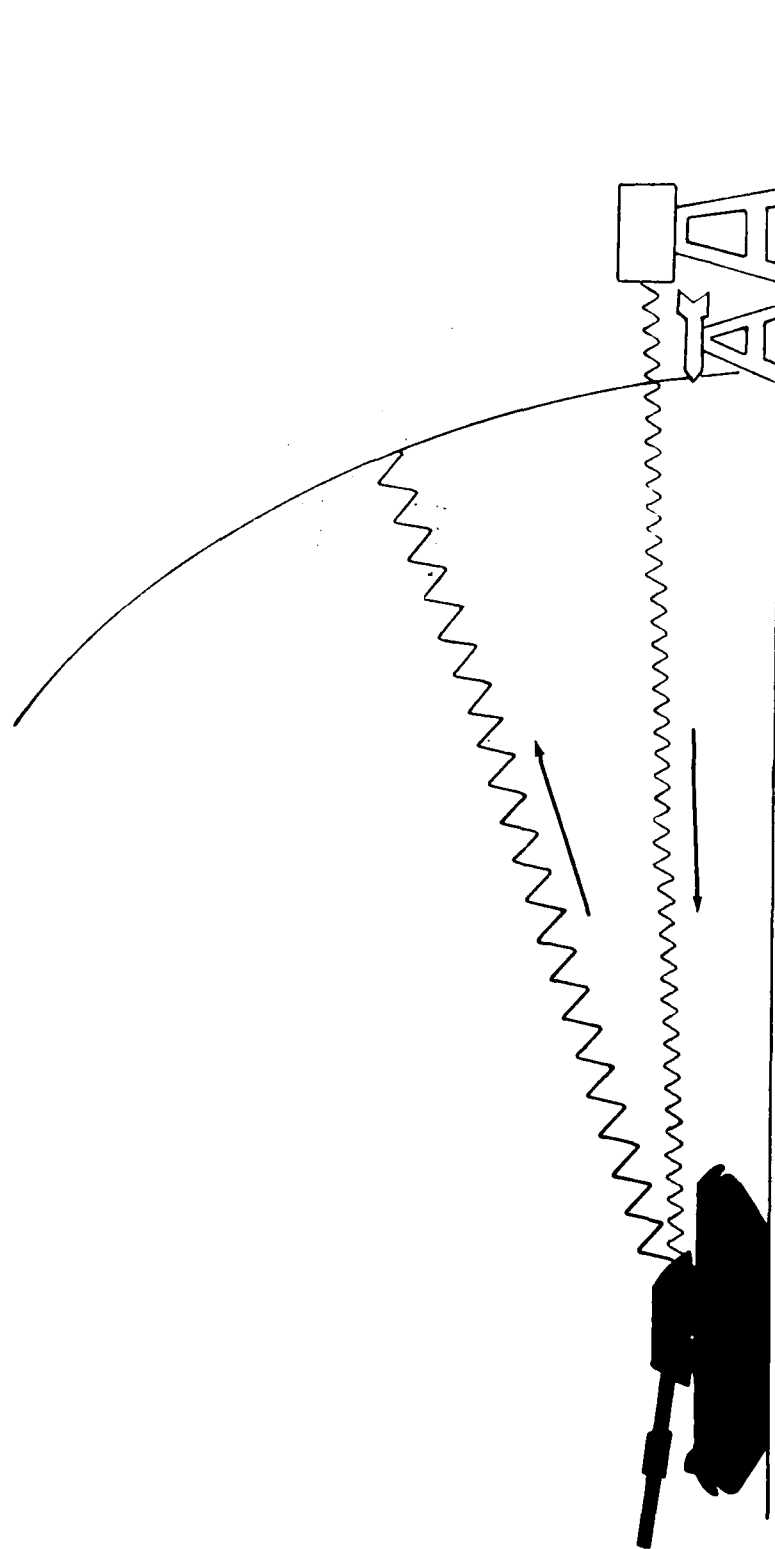- If long irradiation times are anticipated, use a seeker which operates in the vicinity of two μm.
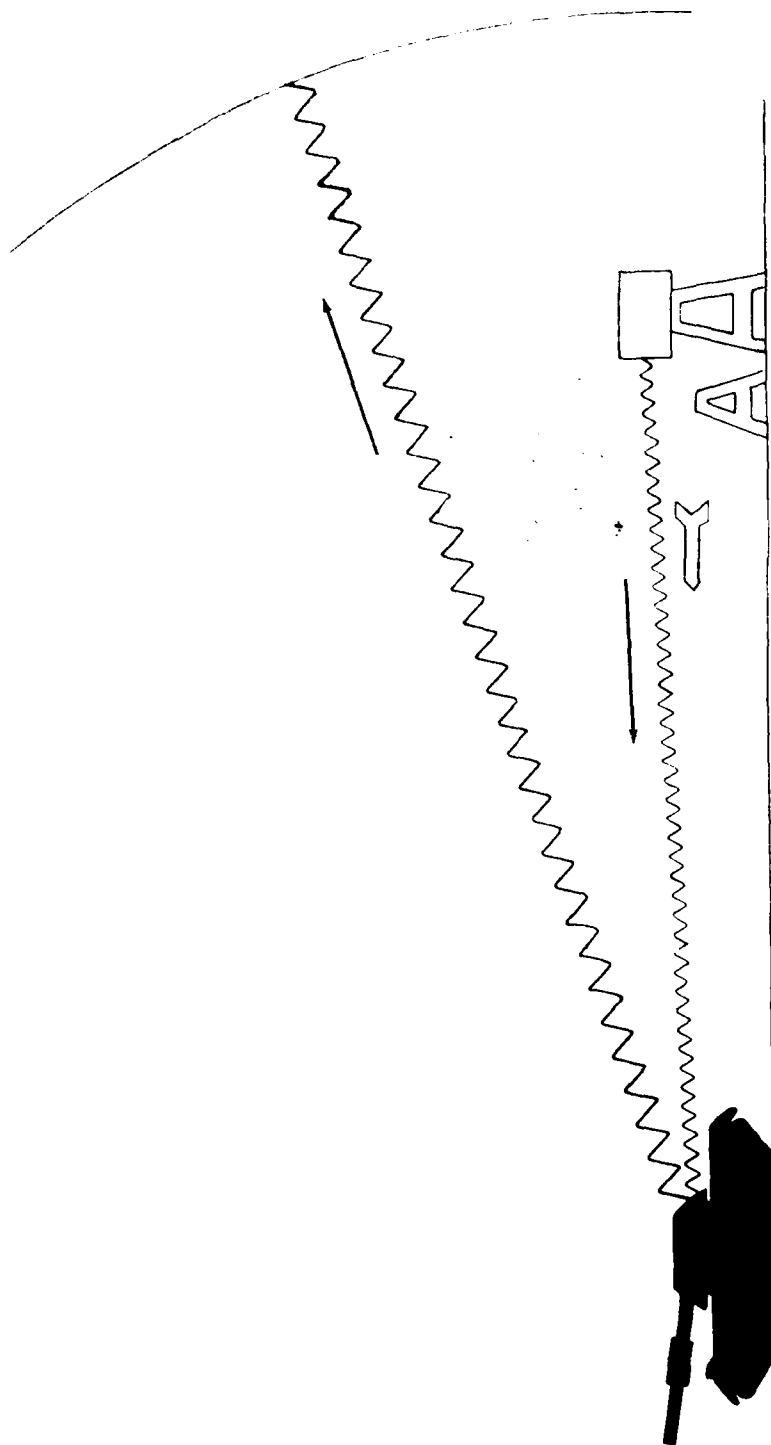
Figure 1.   Model at time of launch.

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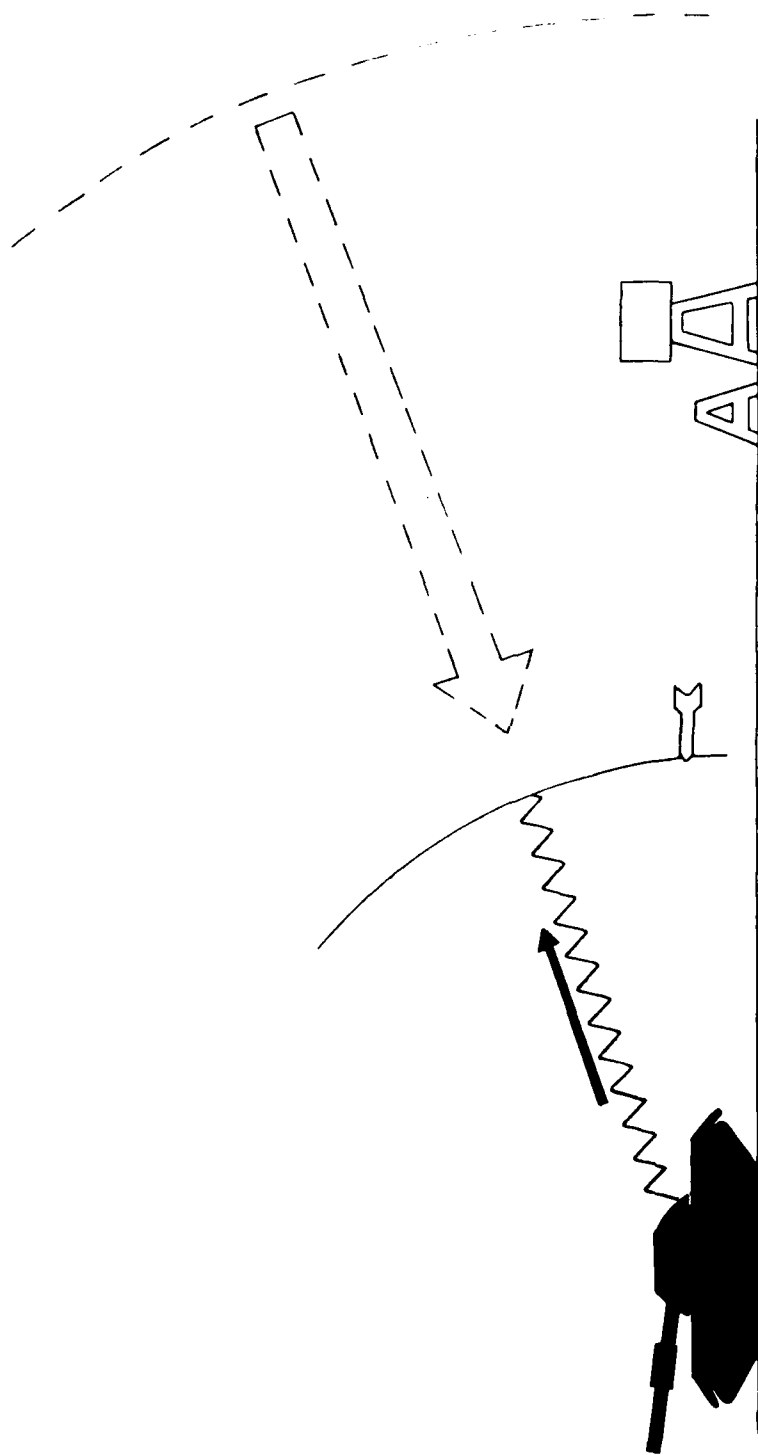**Figure 2. Model at time of laser cutoff.**

Figure 3. Model at the critical point.
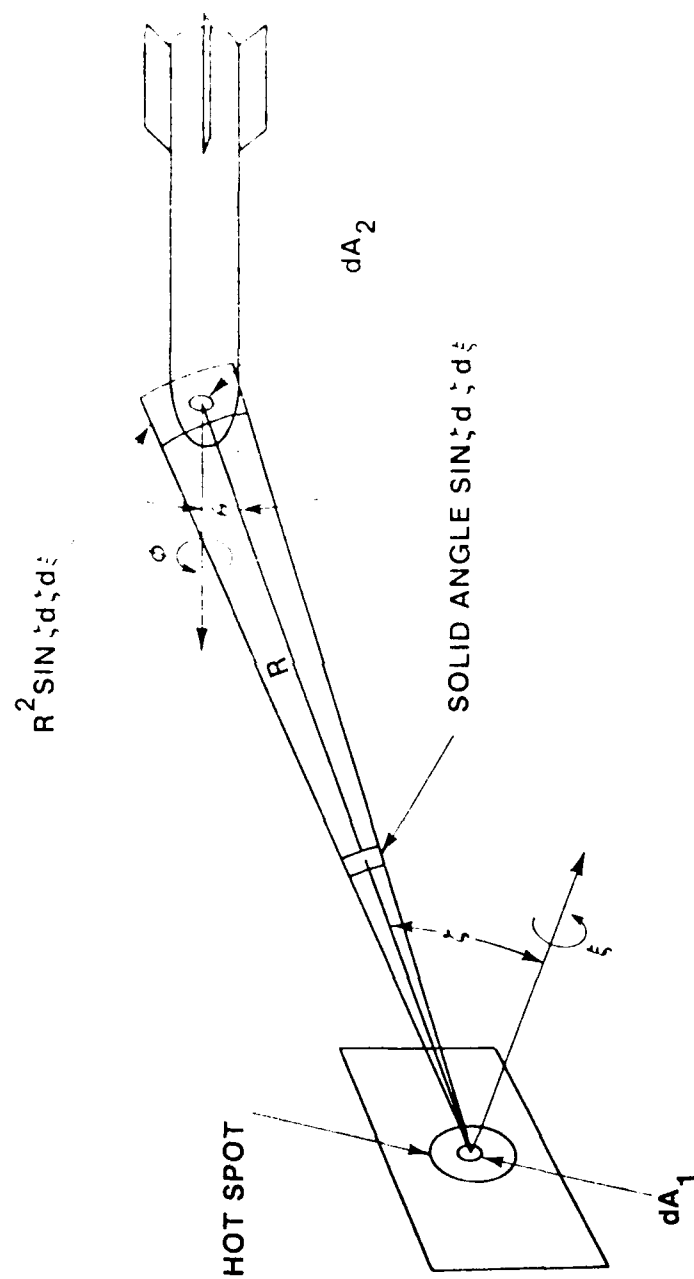
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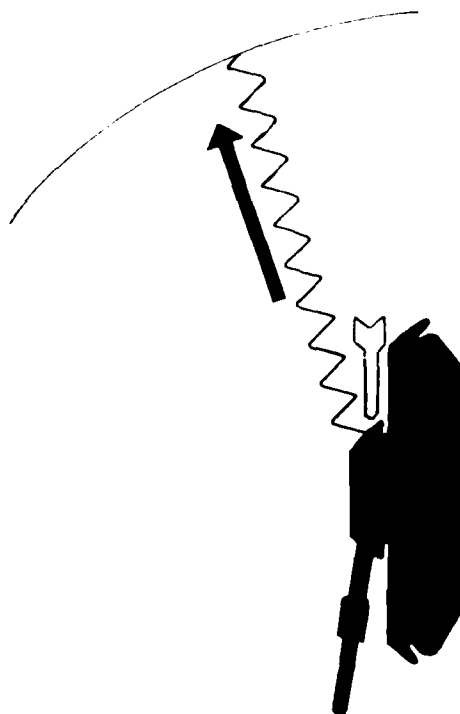
Figure 4. Model at the moment of impact.
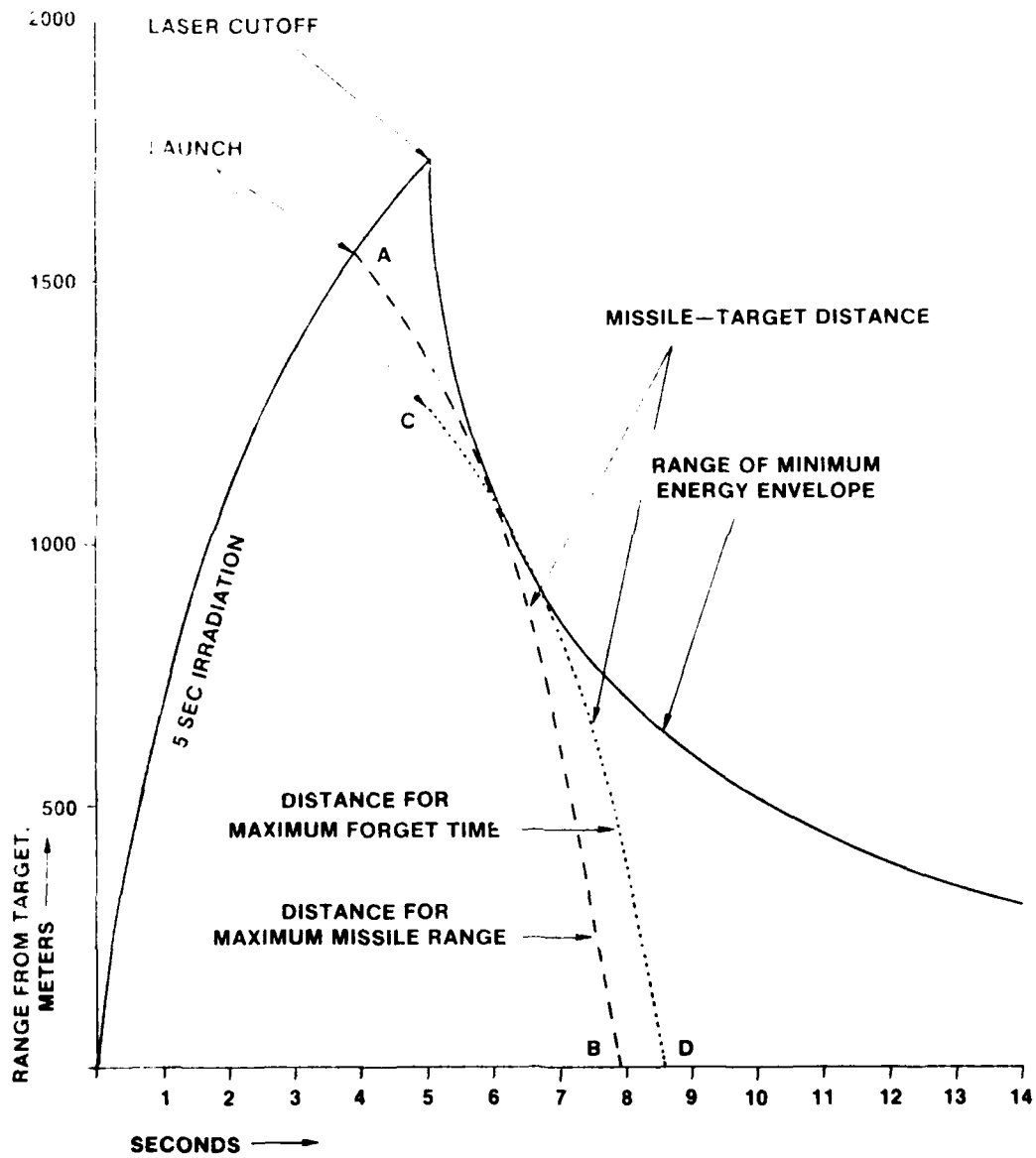
Figure 5. Heat-seeking missile approaching a hot spot

Figure 6. Example plot of missile flights for maximum range and maximum forget time.

Figure 7. Fire-and-forget capability.

SIGNAL-TO-NOISE 1
5CM SPOT 50kW 30
ABSORPTIVITY 0.5
SEEKERλ 4-4.8μ
HAZY WEATHER

1000m RANGE

1500m RANGE

2000m RANGE

BURN

FLIGHT TIME

BURN TIME

FLIGHT TIME

BURN TIME

FLIGHT TIME

SECONDS

1   2   3   4   5   6   7   8   9   10

17
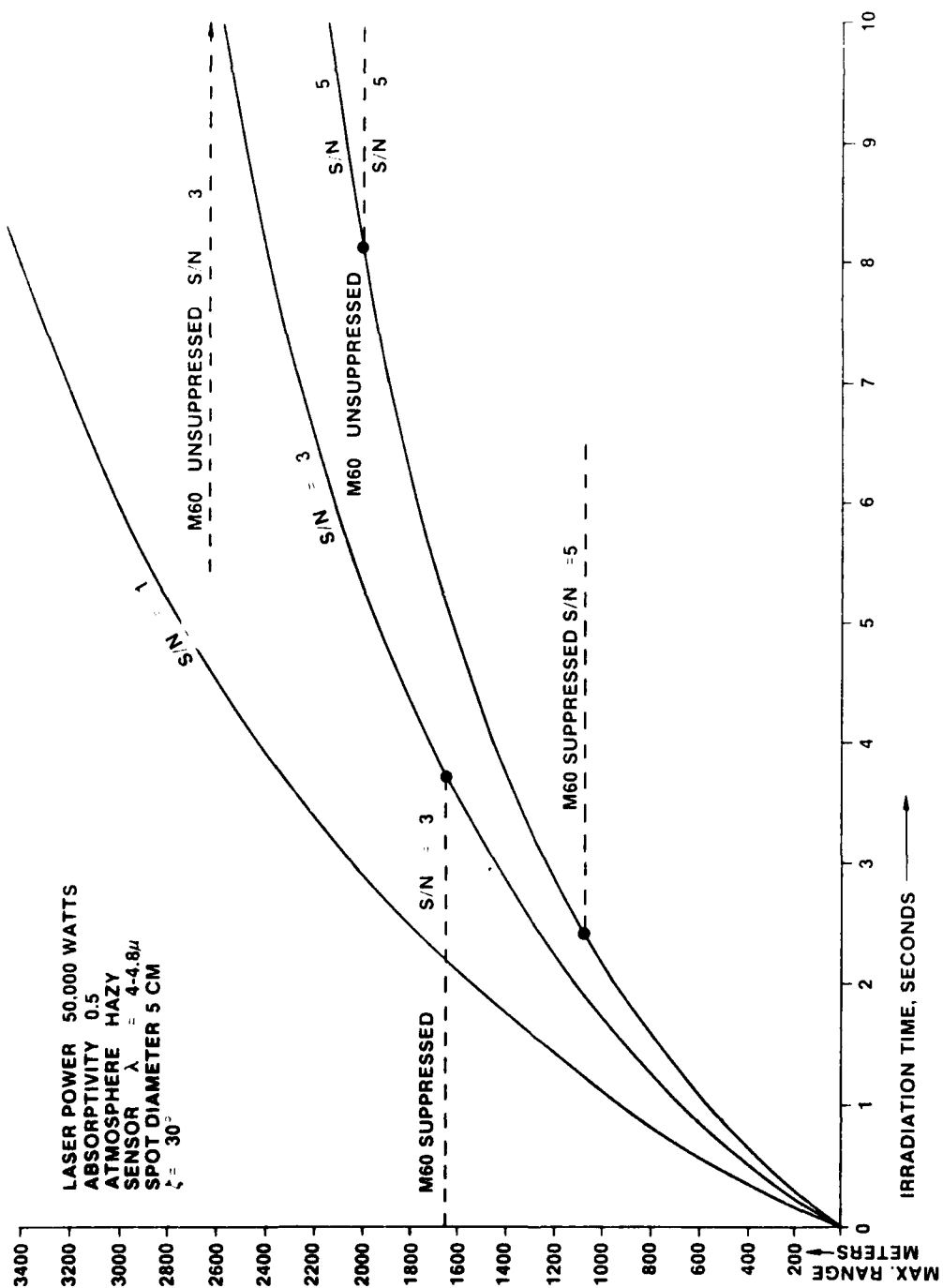
Figure 8. Effect of signal-to-noise ratio on maximum range.

LASER POWER 50,000 WATTS
ABSORPTIVITY 0.5
ATMOSPHERE HAZY
SENSOR λ = 4-4.8μ
SPOT DIAMETER 5 CM
ζ = 30°

MAX. RANGE METERS

IRRADIATION TIME, SECONDS

M60 UNSUPPRESSED S/N = 3

S/N = 3

S/N = 1

M60 UNSUPPRESSED

S/N = 5

S/N = 5

M60 SUPPRESSED S/N = 5

S/N = 3

M60 SUPPRESSED
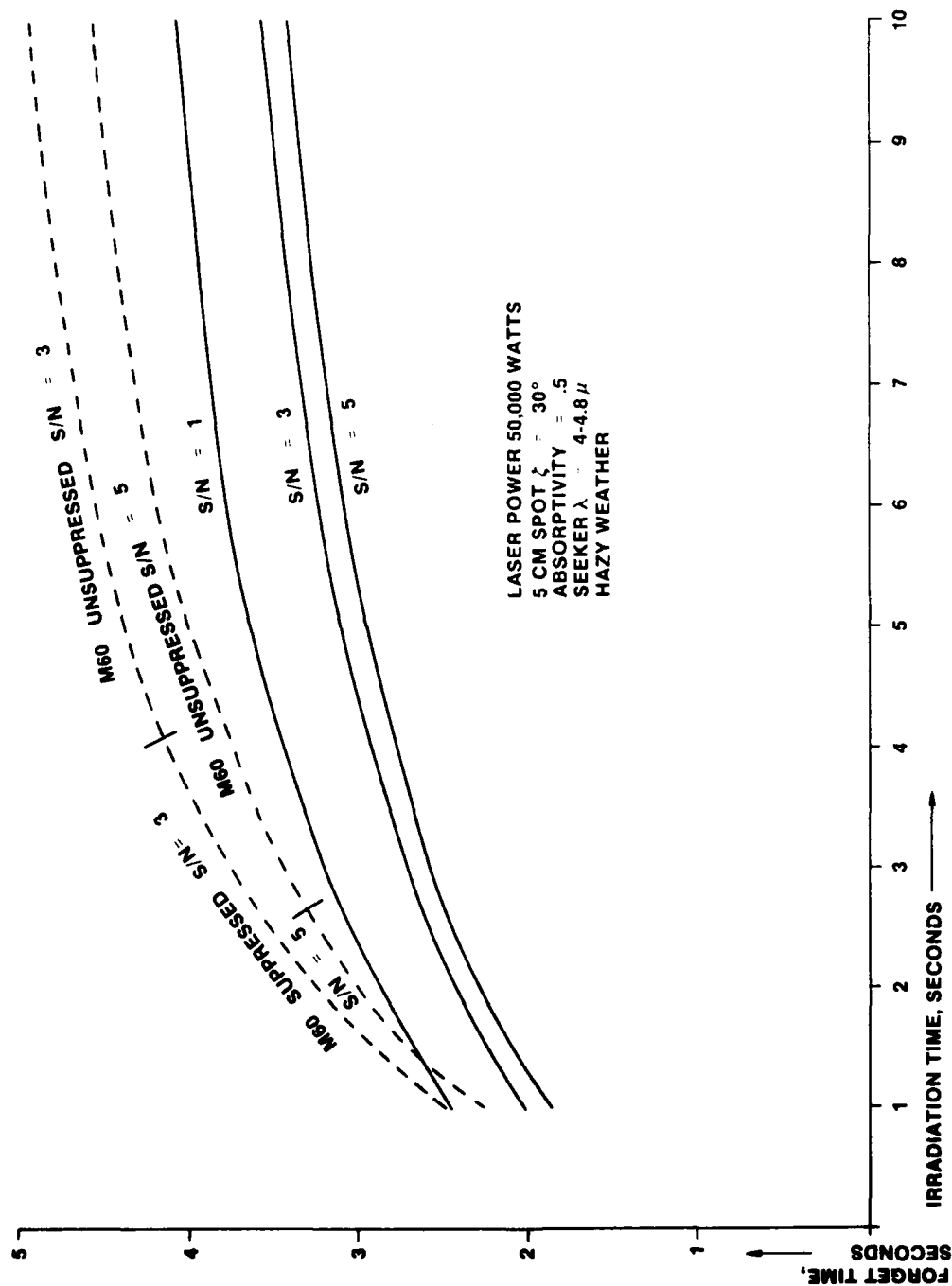
Figure 9. Effect of signal-to-noise ratio on forget time.

LASER POWER 50,000 WATTS
5 CM SPOT ζ = 30°
ABSORPTIVITY = .5
SEEKER λ 4-4.8 μ
HAZY WEATHER
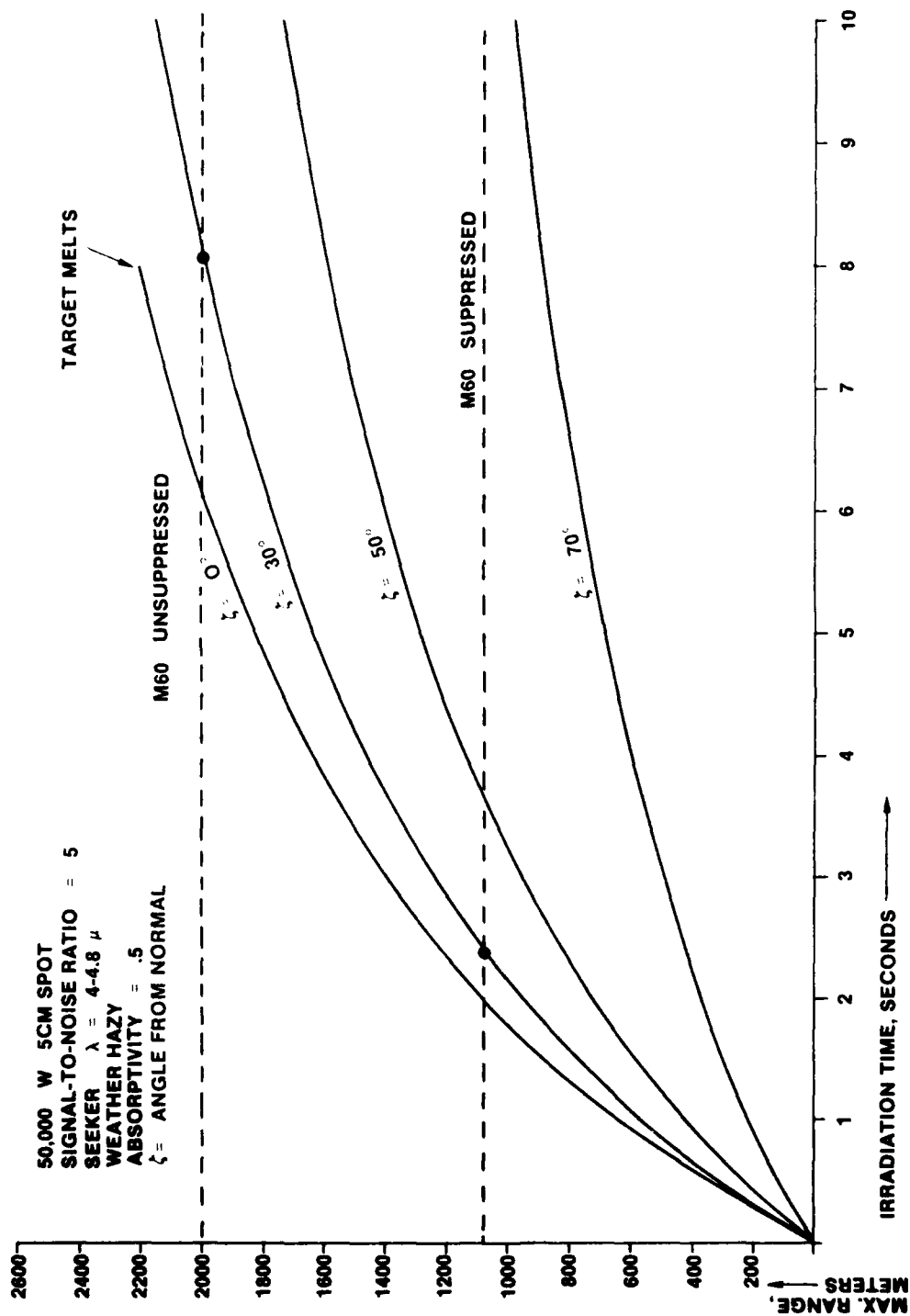
Figure 10. Effect of the angle of incidence on maximum range.
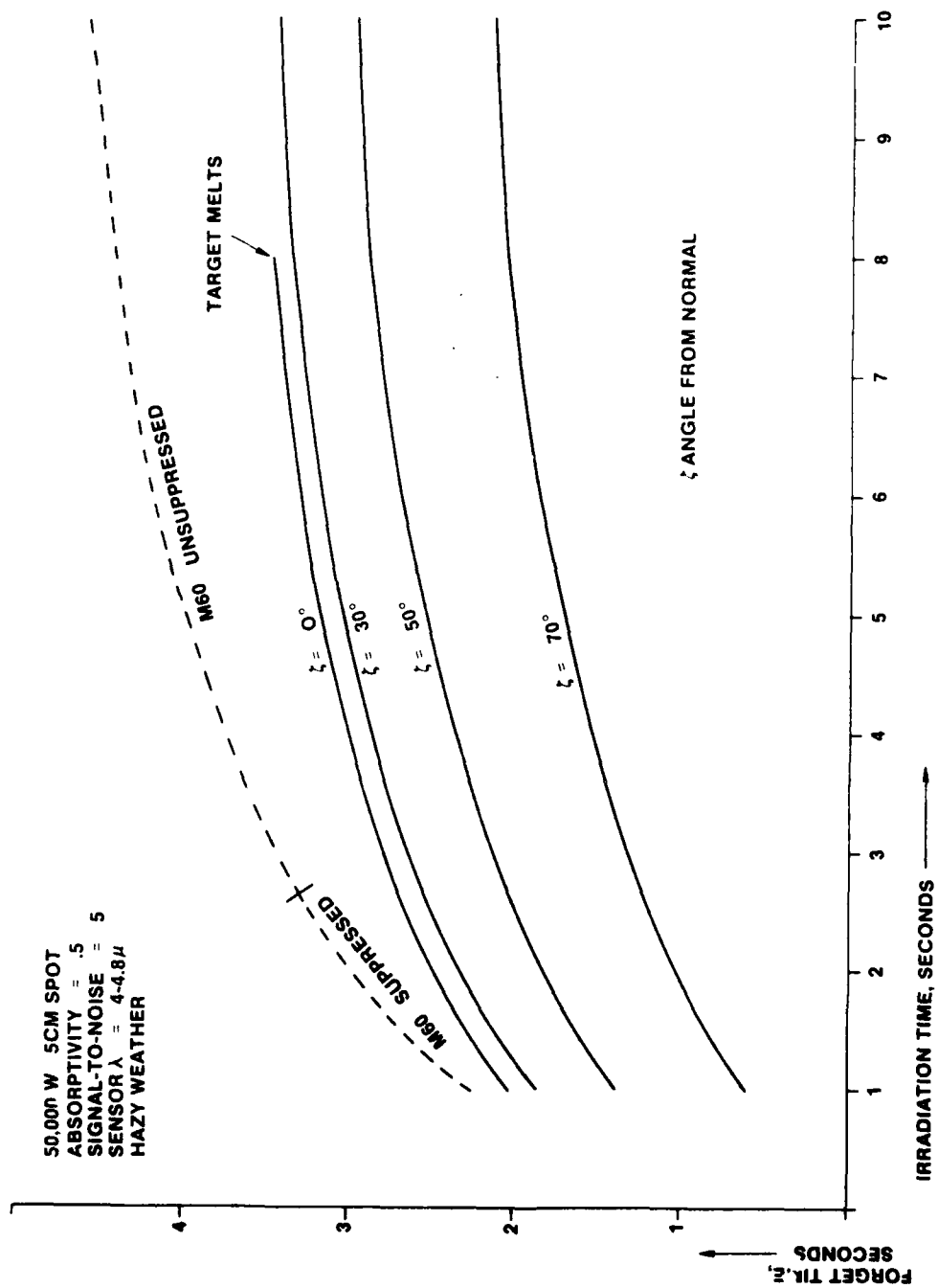
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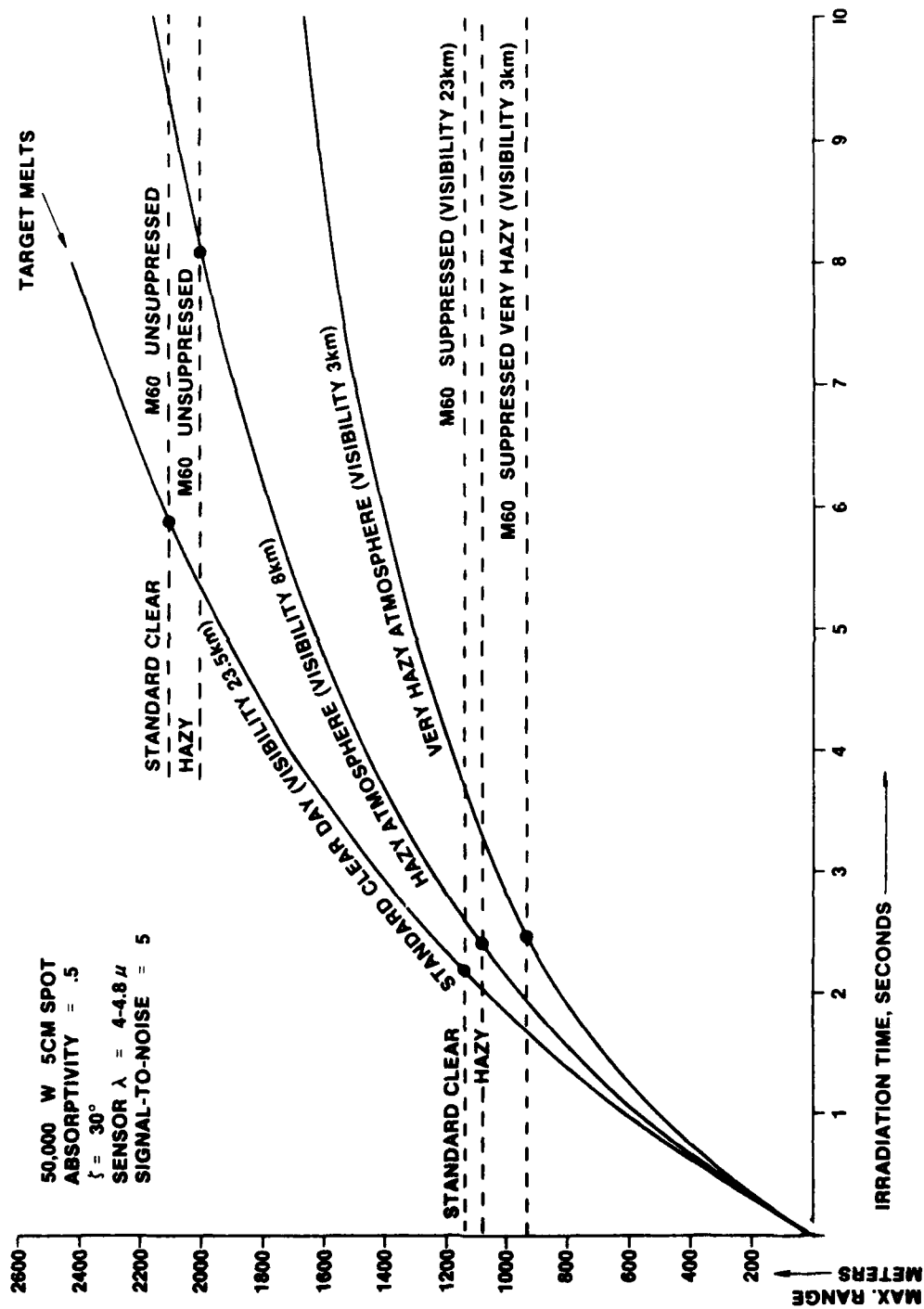Figure 11. Effect of angle of incidence on forget time.

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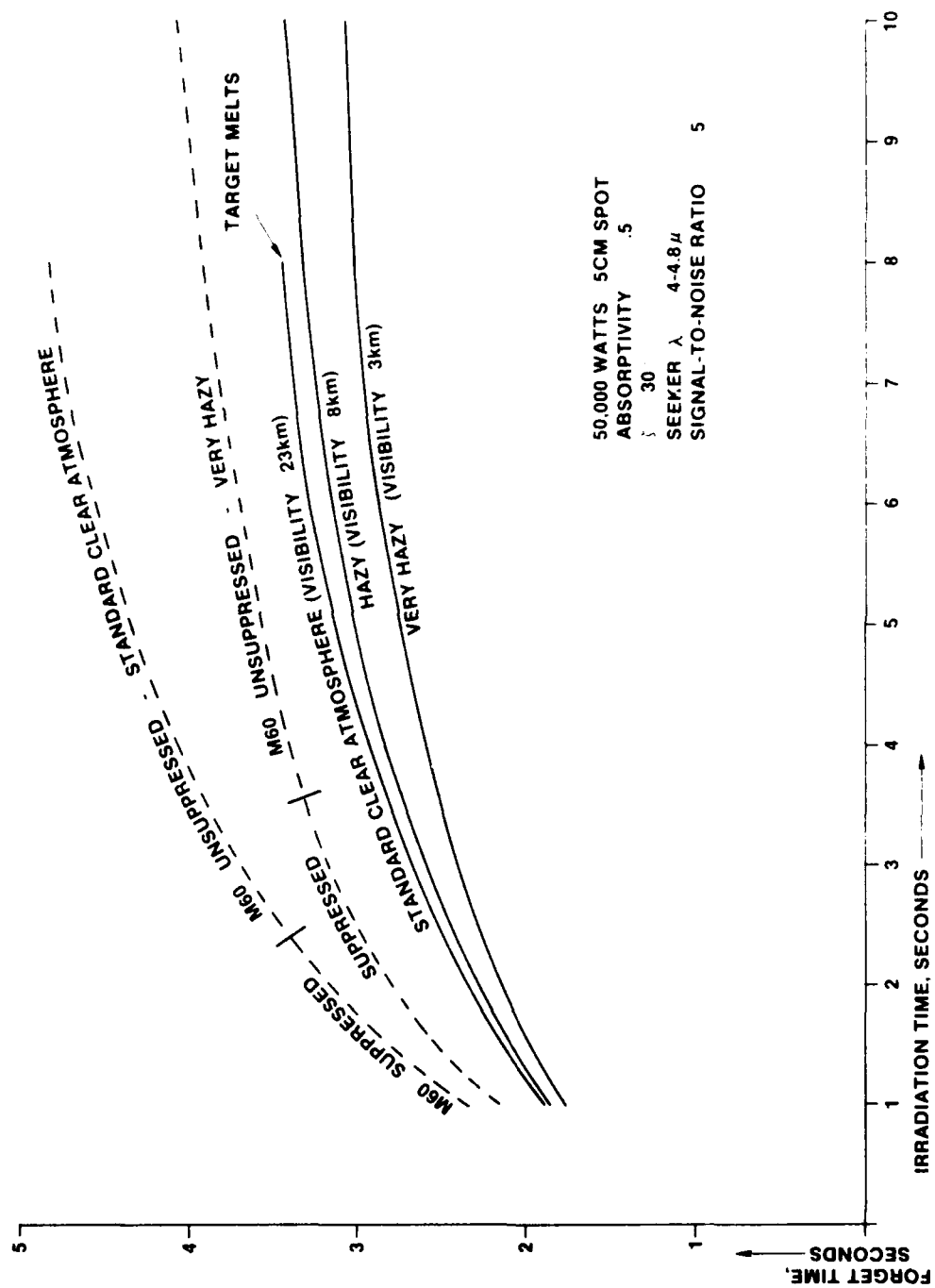Figure 12. Effect of weather on maximum range.
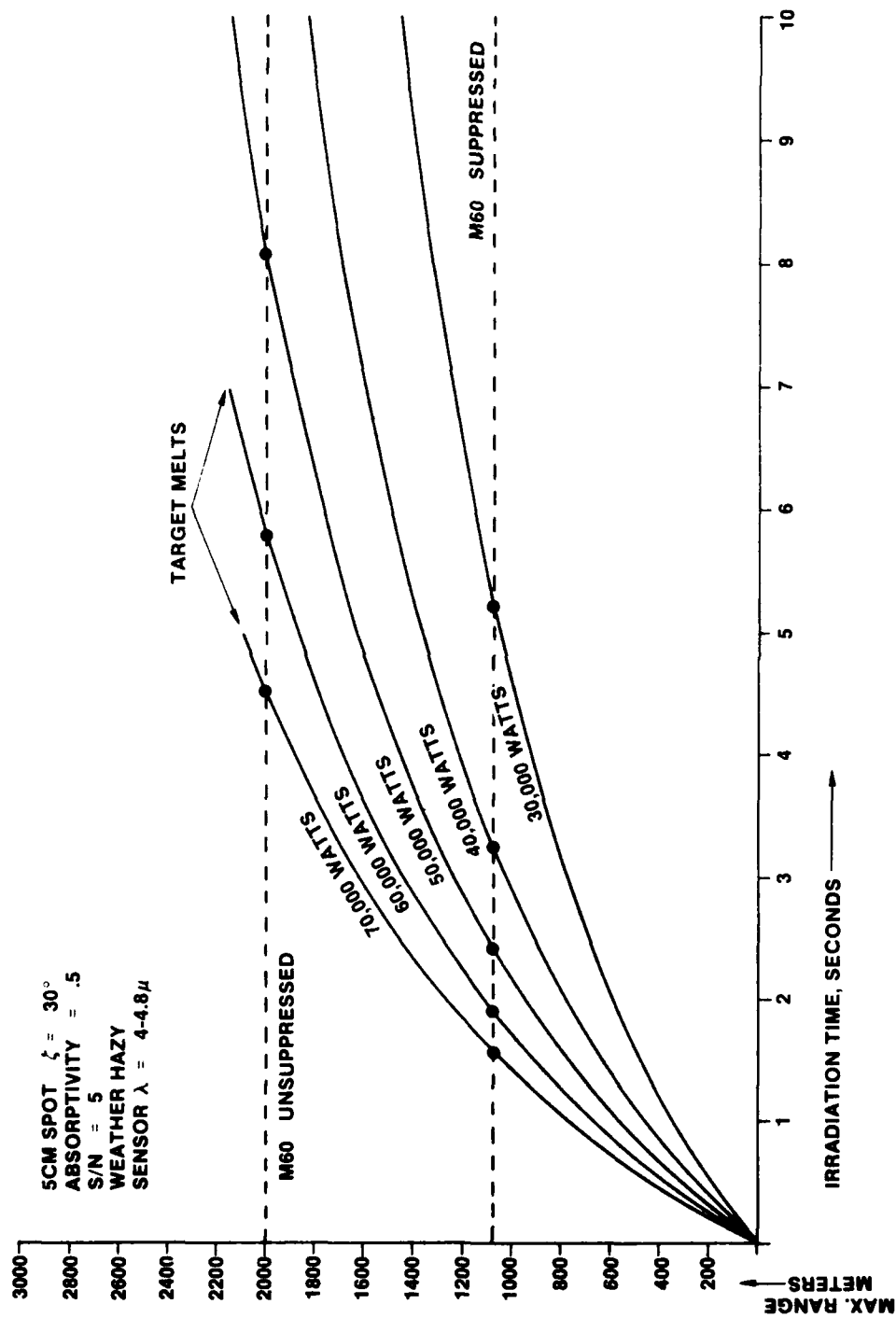
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Figure 13. Effect of weather on forget time.

Figure 14. Effect of irradiation times at various power levels-maximum range.
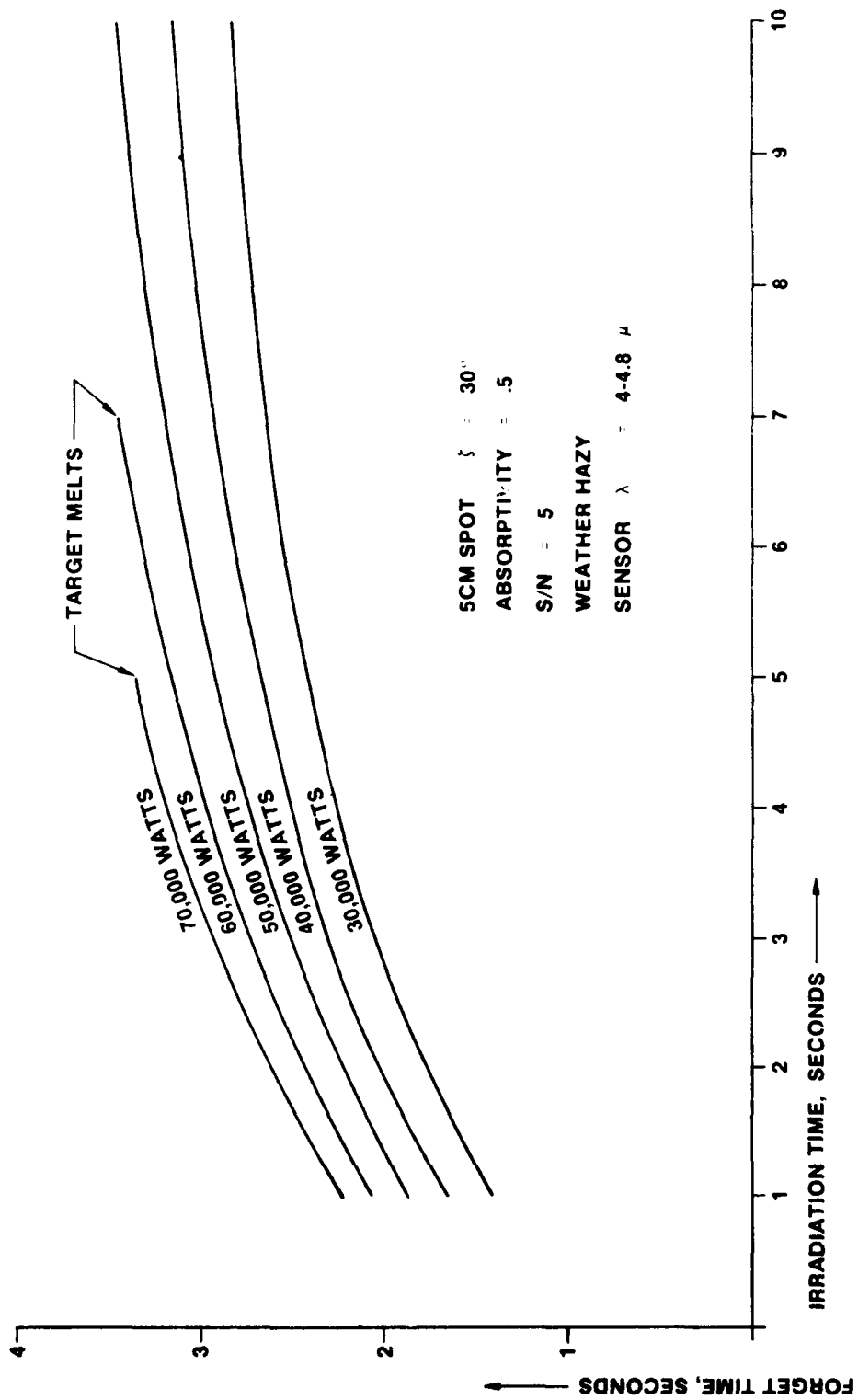
Figure 15. Effect of irradiation times at various power levels - forget time.
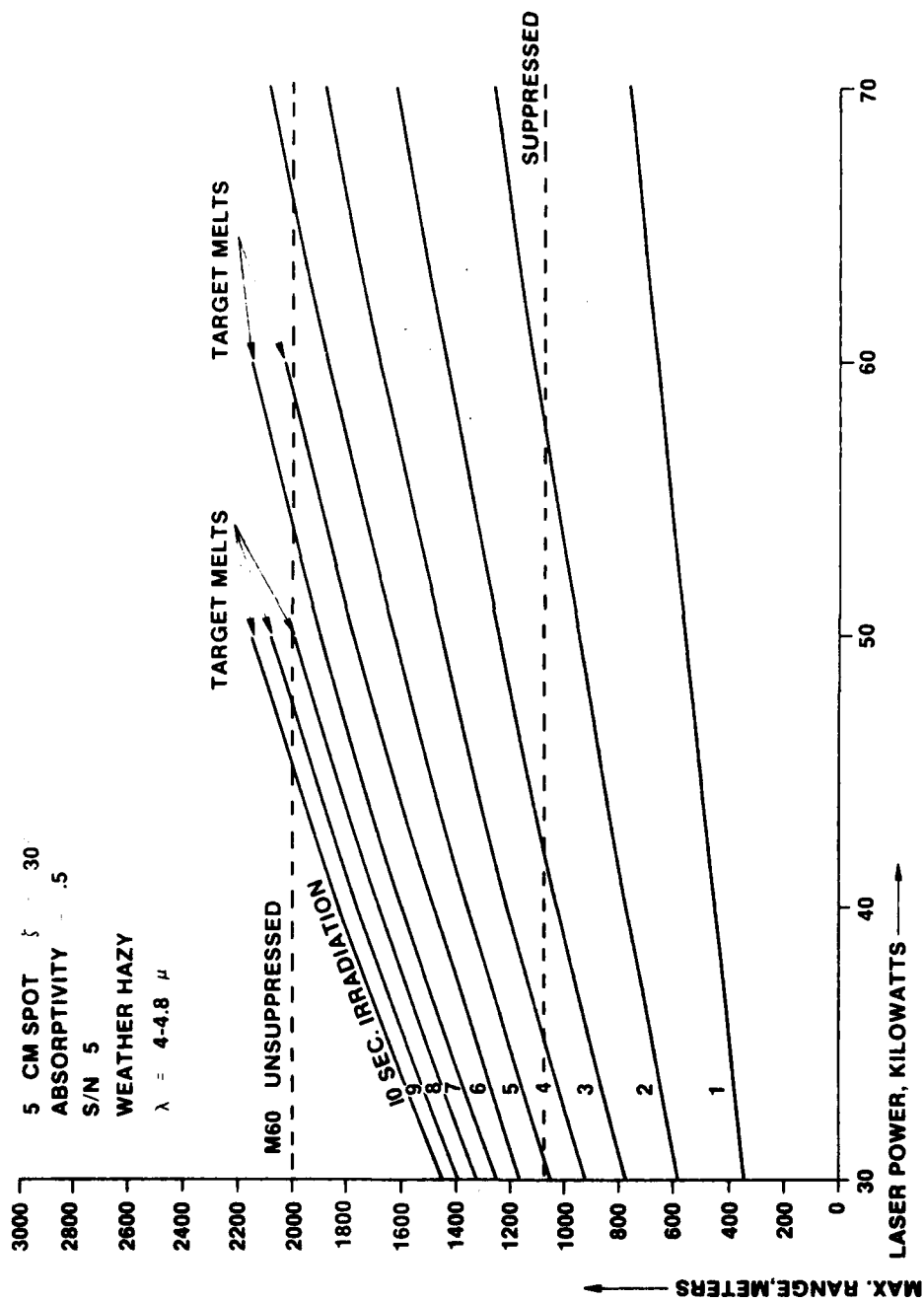
70,000 WATTS
60,000 WATTS
50,000 WATTS
40,000 WATTS
30,000 WATTS

TARGET MELTS

5CM SPOT $\zeta = 30°$
ABSORPTIVITY = .5
S/N = 5
WEATHER HAZY
SENSOR $\lambda = 4$-4.8 μ

IRRADIATION TIME, SECONDS

FORGET TIME, SECONDS

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Figure 16. Effect of power at various irradiation times.
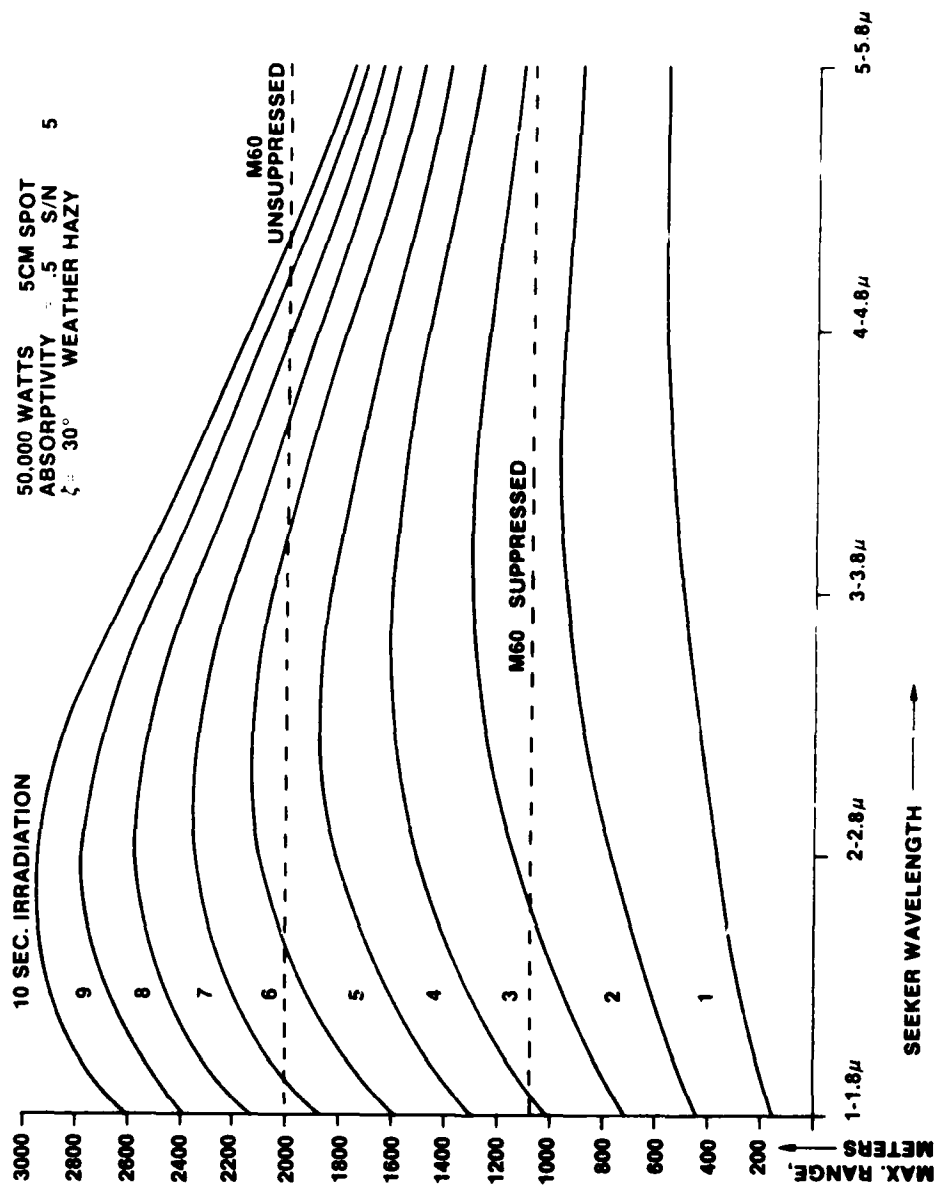
Figure 17. Effect of seeker wavelength for various irradiations.

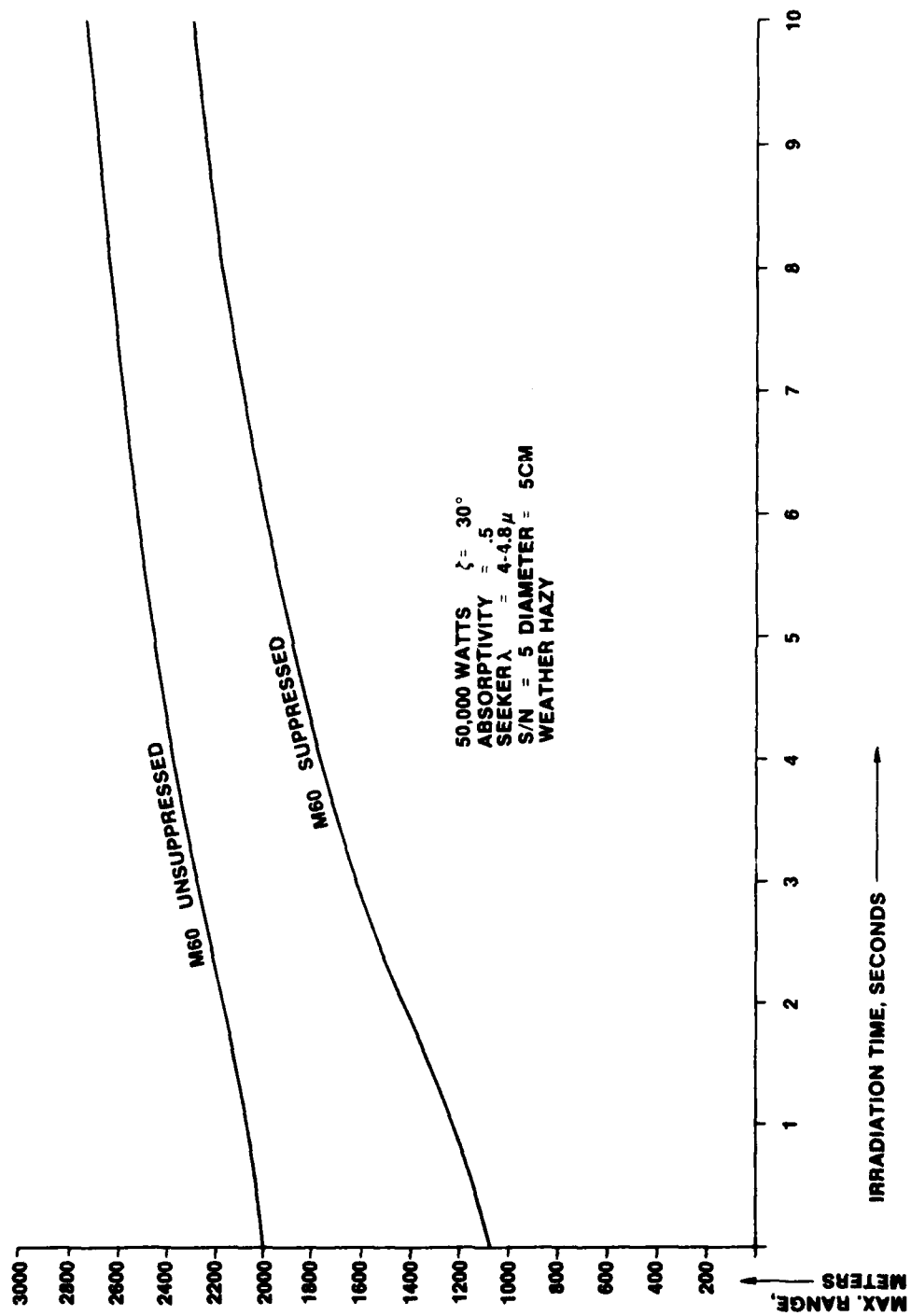Figure 18. Effect of supplementing the signal from a hot tank.

50,000 WATTS $\zeta = 30°$
ABSORPTIVITY = .5
SEEKER λ = 4-4.8μ
S/N = 5 DIAMETER = 5CM
WEATHER HAZY

M60 UNSUPPRESSED

M60 SUPPRESSED

IRRADIATION TIME, SECONDS →

MAX. RANGE, METERS

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